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Design Algorithm for Optimum Capacity of ESS Connected With PVs Under the RPS Program

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Dedicated to Dr. Sehwan Ryu.

ABSTRACT A distributed power generation system uses an intermittent power source that provides low power. Furthermore, it cannot be centrally controlled from the perspective of the system operator. The photovoltaic (PV) power generation system is installed with an energy storage system (ESS) to increase the power source quality compared to that possible with PV-only power generation. In this paper, an estimation algorithm is proposed for improving battery capacity to construct a suitable and economical system. In addition, an optimal algorithm is proposed that considers different factors. For example, the cost of constructing the battery and the amount of electric power sales reflecting the renewable energy certificate weighting factor of 5.0 are based on the cost of the battery construction, depth of battery discharge, charge/discharge cycle of the battery, cost of the energy conversion device, operation maintenance cost, and charge cycle of the battery. The optimized battery capacity is calculated by considering the correlation between PV power and meteorological parameters, construction cost, and the benefit of the amount of electricity sold, with an error rate of 5.75%.

INDEX TERMS Design algorithm, energy storage system (ESS), optimum ESS capacity, renewable energy certificate (REC) weighting factor, renewable portfolio standard (RPS).

I. INTRODUCTION

Renewable portfolio standards (RPS) are currently implemented widely to increase the use of renewable energy in Korea. PV power generation facilities that are easy to install and maintain are attracting attention under the RPS. However, PV power generation takes place for only 4 h per day, and hence is not a suitable power generation method from the utility company's perspective. To overcome this shortcoming, the efficiency of the system operation is improved by using an energy storage system (ESS) that stores the generated electric power and discharges during times when power is not generated.

Several previous researches have been conducted on the ESS, and different types of ESS have been compared. Various types of storage methods having different electricity storage techniques have been developed [1]. The battery energy storage system responds to the power demand very quickly, and it smoothens the fluctuations in the PV or wind power, by adopting the status of charging (SOC) control strategy [2]. The market participation based on different firming control strategies of intelligent PV power plants was proposed to optimize the economic exploitation based on the storage system management considering PV generation predictions [3]. The ESS system can be applied to vehicles, utilities, and renewable energy sources [4]. A residential battery energy storage system can also be applied by solving the convex programming problem to respond to the load variations in a home [5], [6]. The energy exchange between a PV power generation system and the main grid has also been analyzed. Particular attention has been given to the optimization of the renewable energy management to supply power to the microgrid loads and increase the PV energy self-consumption rate [7]. Among the ESS control methods, rule-based control for dispatch and hourly control have been compared to reduce power variations [8]. The real-time decentralized demand-side management to adjust the real-time residential load to follow preplanned day-ahead energy generation by the microgrid has also been proposed [9]. A control strategy for achieving the optimum use of battery energy storage has been suggested [9]. Determining the size of the ESS connected with a PV power generation system is studied to supply the demand from loads [11]. The PV electricity sales price is determined by the sum of the system marginal price (SMP) and the renewable energy certificate (REC). The SMP is the same concept as the electric wholesale unit price and the REC is the incentive for using the renewable energy supply. At the end of 2016, the government announced that ESS energy sources associated with PV power should be weighted 5.0 times for the REC for the efficient use of the energy source and the stable operation of the system. This policy was planned to continue until June 2018 [12]. Because of the price of the battery that accounts for more than 70% of the price of the ESS, constructing an economical system configuration is difficult. Therefore, a battery capacity estimation algorithm is proposed in this study to construct the most suitable and economical system and the accuracy of the algorithm is confirmed by comparing several factors. For example, the cost of constructing the battery and the amount of the electric power sales reflecting the REC weighting factor of 5.0 are based on the cost of battery construction, battery depth of discharge, battery charge/discharge cycle, cost of the energy conversion device, operation maintenance cost, and charge cycle of the battery. Furthermore, the power flowing into the ESS is calculated using the algorithm designed to determine the correlation between the PV output and multiple variables, including the weather conditions regardless of the region in the world.

II. SYSTEM DESCRIPTION

A. SYSTEM CONFIGURATION

The system studied in this work consists of a PV power generation system and an ESS system. A system for measuring the PV power generated and the ESS charge/discharge is installed. The schematic diagram is shown in Fig. 1.

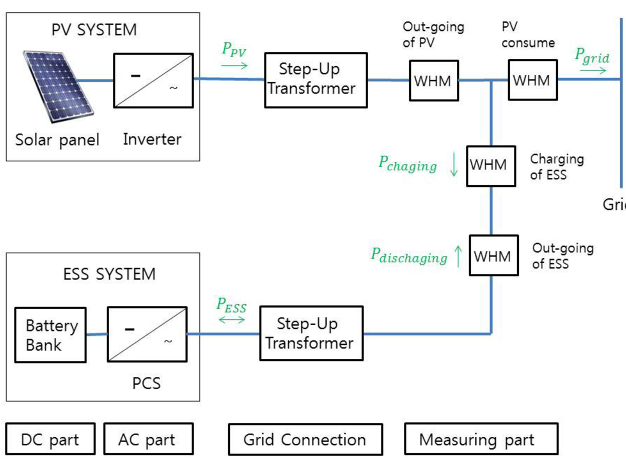

FIGURE 1. Schematic diagram of PV and ESS systems. WHM denotes watt hour meter.

The system consists of a DC part, an AC part, a grid connection device, and a device for measuring the input and output power. The DC power generated by the PV generator is stored in the ESS, and when the ESS battery is charged, the surplus power is transmitted to the grid. The power stored in the ESS is designed to send power to the grid at times when PV power is not generated. This process is performed on a daily basis, and the charging time is from 10:00 am to 4:00 pm. The power provided by the ESS can receive REC weighting, but it must be confirmed and reported to the government energy sectors [12].

B. ESTIMATION OF PV POWER

Several techniques have been proposed for estimating the amount of power produced by PV power generation facilities. Generally, a method for predicting PV power generation with the input factors of irradiation, irradiation time, and ambient temperature provided by a meteorological administration is used.

The irradiation, irradiation time, and ambient temperature applied to the PV power generation forecast have the greatest correlation with the amount of power generated [13]. Therefore, even if the irradiation and the ambient temperature are applied only to the prediction of power generation, there is no significant change in PV power output. The irradiation data provided by the meteorological agency is usually provided in [MJ/m^2]. By conversion of this value to the amount of power from the irradiation data, the daily irradiation data are converted into daily solar energy as follows:

$$1[\mathrm{MJ}/m^2] = 1/3.6[kWh/m^2]. \quad (1)$$

The estimated daily PV power capacity can be obtained using the meteorological data and expressed as follows.

$$P_{PV} = \frac{S}{3.6 \times i} \times A_{module} \times N \times \eta_{module}[kWh/day] \quad (2)$$

In (2), S is the daily irradiation data provided in [MJ/m^2], A_{module} is the area of the PV module, N is the number of the PV modules, η_{module} is the energy conversion efficiency of the PV module, and i is the climate variation factor that affects the PV power related to environmental matters such as clouds, fog, etc. Because PV power generation uses semiconductor devices, power generation is reduced as the temperature increases. The output of the PV power generator according to the change in temperature is expressed as follows.

$$P_{PV}(t) = PV_{max.ref}\frac{G_T}{G_{ref}}(1 - \beta(t_m - 25)) \quad (3)$$

In (3), $PV_{max.ref}$ is the maximum PV power under STC conditions (AM 1.5G, 1000 W/m^2, 25°C), G_{ref} is 1,000 W/m^2, G_T is the plane of array irradiation, β is the temperature coefficient of peak power [%/°C], and t_m[°C] is the surface temperature of the solar module under operating conditions [13].

Fig. 2 shows an example of daily irradiation and average temperatures for four seasons in 2016, the data for one day of which are used in the calculation as input parameters.

The PV power is proportional to irradiation, but P_{MAX} changes according to the ambient and module temperatures. Fig 3 illustrates daily power versus temperatures in winter

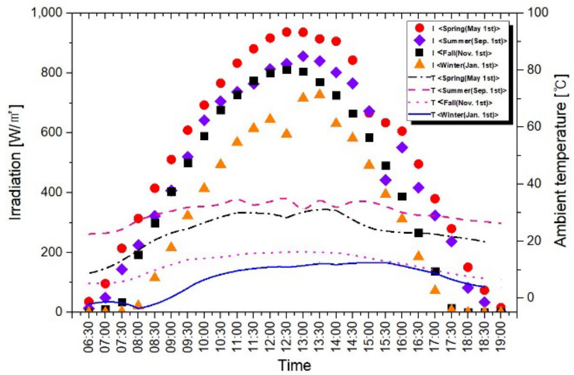

FIGURE 2. Daily irradiation and temperature for the input parameters.

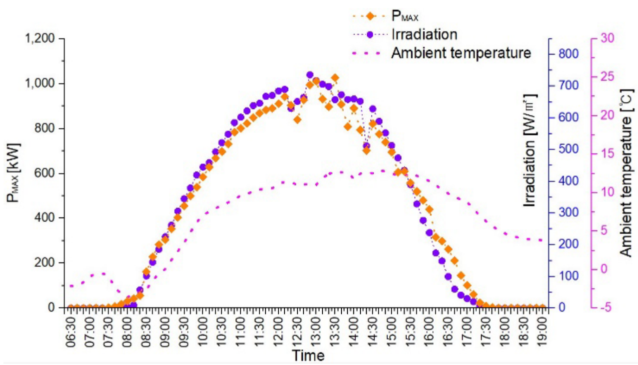

FIGURE 3. Maximum power and irradiation versus temperature characteristics.

time showing that P_{MAX} in the morning decreases as the temperature increases whereas irradiation increases to validate the use of (3).

In this study, the correlation coefficient was analyzed to investigate the relationship between power generation and meteorological factors. The correlation coefficient is a method of determining the strength of the relation between two variables [14]. In (4), $\bar{x}$ and $\bar{y}$ are the means of the population, and the correlation coefficient R has a value of $+1$ if the two variables are equal, 0 if they are different, and -1 if they are opposite. In Fig. 4, the upper part of the graph is the correlation coefficient and the lower part is the point graph. The diagonal line is the histogram [15]. An analysis of PV power considering the meteorological factors confirmed that the plane of array irradiance (POA) and PV module temperature T_m critically influence the generation whereas ambient temperature T_a and global horizontal irradiation (GHI) influence less, as Fig. 4 shows. This correlation is expressed in (5). Fig. 5 shows the mean average percentage errors (MAPE) [%] of PV power [kWh], calculated by using (5), ranging from 10.5 to 15% approximately.

$$R = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{4}$$

$$P_{PV_{reg}} = POA\,[1.553 - (6.521e-03) * T_m] \tag{5}$$

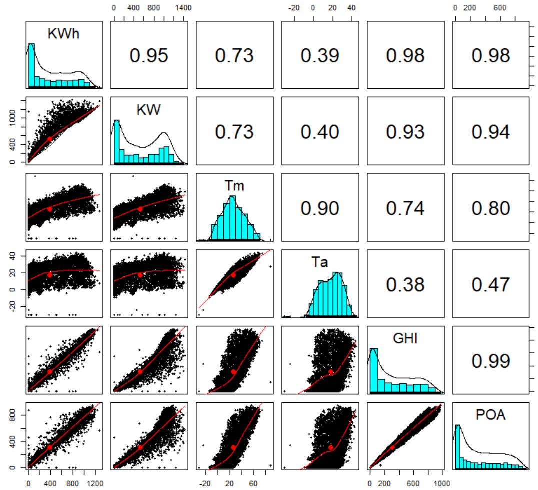

FIGURE 4. Pairs plot showing correlation between PV power and meteorological parameters (temperature [°C] and irradiation [kWh/m^2]).

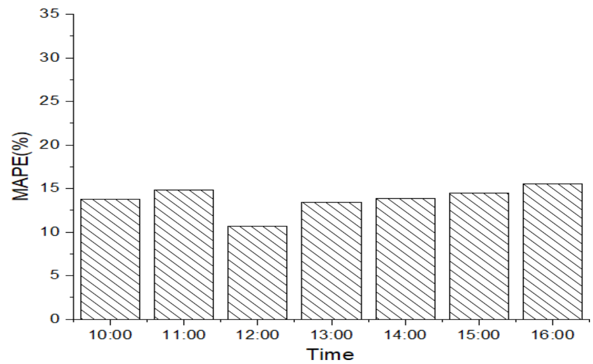

FIGURE 5. Percentage error of modeled (4) in a year (2017).

C. PV CONSTRAINTS

The power produced by the PV power generation system is stored in the battery for a specified time, and the remaining power is sent to the system and discharged at other times. The constraints mentioned above are as follows.

$$P_{PV} \geq P_{ESS} + P_{grid} + P_{loss} \tag{6}$$

$$P_{PV} \geq P_{ESS} + P_{loss} \tag{7}$$

$$P_{PV} = 0 \tag{8}$$

In (6)–(8), P_{PV} is the power generated by the PV power generation system, P_{ESS} is the stored power in the ESS battery, P_{loss} is the system loss occurring during energy conversion, and P_{grid} is the transmitted power to the grid.

If PV power produces more power than the ESS battery capacity, (6) is valid. When the power is the same as the battery capacity, the relationship in (7) is valid. Finally, when the PV power is not generated because of weather conditions, (8) is valid. When the electric power charged in the ESS is the maximum, the electric power transmitted to the system is the highest, and the electric power generated after charging the ESS should be structured to feed power directly into the system. The dispatched power from the ESS to the grid is proportional to the power system, ESS and step-up transformer efficiencies so that it could be

$$P_{discharge} = P_{ESS} \times \eta_{ESS} \times \eta_{TR} \tag{9}$$

where $P_{discharge}$ is the power discharged to the grid, P_{ESS} is the stored power in the ESS, η_{ESS} is the charge/discharge efficiency of the ESS, and η_{TR} is the efficiency of the step-up transformer.

D. ESS SYSTEM CONFIGURATION

1) ESTABLISHMENT OF CHARGING AND DISCHARGING PLAN

The PV power generation time is defined from sunrise to sunset. The PV power is charged from 10:00 am to 4:00 pm and at other times discharged to the grid. The reason for thus limiting the duration is to stabilize the main grid so that this time interval could be changed with different areas that have different insolation environments. The ESS discharging power is weighted to REC prices; hence, the $P_{discharge}$ power price is the highest. Therefore, the daily charge and discharge plan should be optimized in consideration of the input information, control variables, objective function, and constraints. Fig. 6 shows the optimized day plan of charge/discharge [16].

The PV power predicted by statistical methods using the irradiation and module temperature then verifies the reliable output error range. The power conditioning system (PCS) of the ESS manages and determines whether the PV power is stored in the ESS or sent to the grid. The priority rule is the capacity of the ESS. This capacity is schematically expressed by the rectangular area in Fig. 8, and the inside of each output curve indicates the charge amount of the ESS. The area between the power curve and the rectangular area denoting the ESS capacity shows the directly dispatched power to grid. The inner area of the rectangular area and the power curve represents the output of P_{ESS} in Fig. 8.

2) COMPARISON WITH BATTERY PERFORMANCE

Recently, ESS systems have been used for connecting wind power plants, PV power generators, the grid, and emergency generator replacements. The convergence of wind and PV power generation systems is crucial for connecting these systems to the grid and improving the economy and system stability.

Batteries are the main part of the ESS system, and lead–acid batteries and lithium-ion batteries are the most widely used. In Korea, lithium-ion batteries are accepted in the weighted application system. In this paper, we compare the economic characteristics of lead–acid and lithium-ion batteries, considering their charging functions, discharging functions, and life cycles, listed in Table 1 [17].

The major point to consider is the number of charge and discharge cycles, which affects the replacement cycle of the battery.

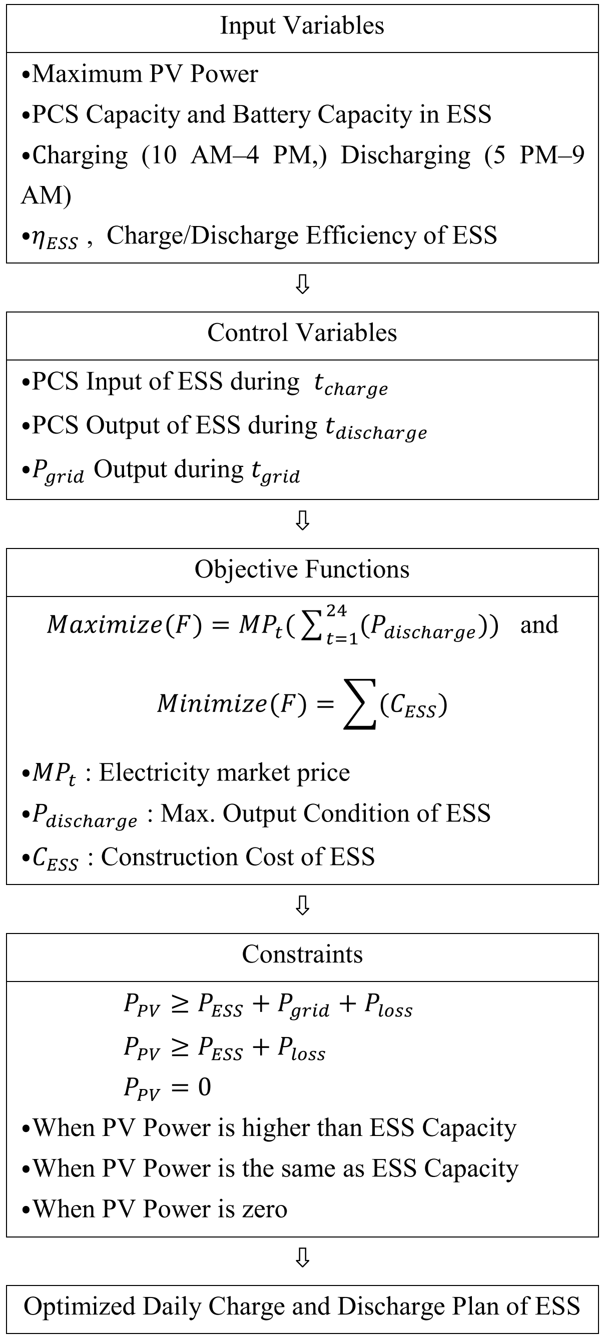

FIGURE 6. Daily ESS plan for charge and discharge.

3) DETERMINATION OF POWER CONDITIONER

The PCS is in charge of controlling the charging and discharging of the battery [18]. The PCS, which is the part of the ESS associated with PV power generation, allows charging of the battery at the appointed hours and discharging the power into the grid. These events are recorded and reported. To carry out all of these processes, determining an optimum capacity and a proper specification for the photovoltaic capacity is necessary.

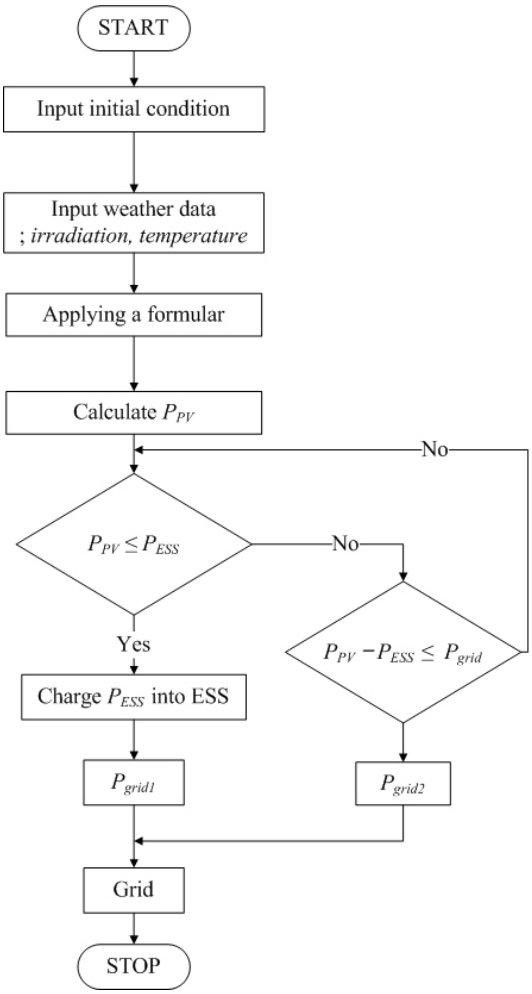

FIGURE 7. Flow Chart of PV power and ESS system.

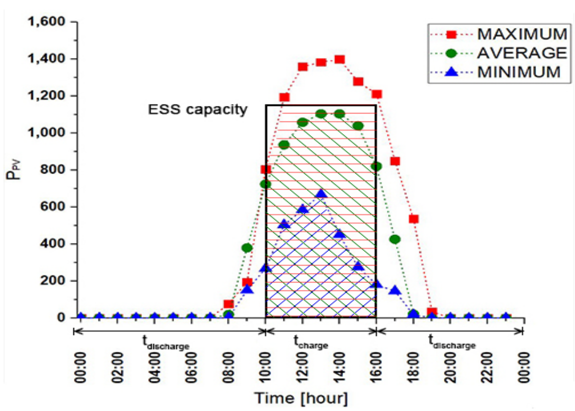

FIGURE 8. Schematic diagram of charging/discharging interval and ESS capacity.

III. ESTIMATION OF ESS SYSTEM

A. COST OF ESS AND BATTERY

The construction cost of the ESS used in PV power generation is composed of the costs of the PCS, the battery, operations and maintenance (O&M), battery replacement, battery management, energy management, and system construction. Other charges, such as charge/discharge loss, energy conversion loss, etc. are not considered because these items are negligible in comparison. All costs of construction and O&M costs are expressed as the net present value (NPV) as follows by (10) [19].

TABLE 1. Comparison of lead–acid battery and lithium-ion battery.

Item	Lead-Acid	Lithium-Ion
Nominal Cell Voltage [V]	2.0	3.7
Energy Density [Wh/kg]	25–50	75–200
Power Density [W/kg]	75–300	500–2000
Cycle Life (100% DoD)	200–1,000	1,000–10,000
Capital cost [US$/kWh]	100–300	300–2,500
Round-trip Efficiency [%]	75–85	85–97
Self-discharge	low	Medium

$$NPV_{cost} = \sum_{k=1}^{n} \frac{C_k}{(1+t)^k} - C_0 \tag{10}$$

where C_k is the future cost of the equipment during its lifetime, t is the interest rate, n is the lifetime of the system, and C0 is the total cost of the ESS in the first year of construction. When investing in power industry facilities, the cost of the battery is estimated by evaluating cost effectiveness using the levelized cost of energy (LCOE) [20].

$$\text{LCOE} = \frac{\sum_{k=1}^{n} \frac{I_k + M_k + I_a}{(1+i)^k}}{\sum_{k=1}^{n} \frac{E_k}{(1+t)^k}}, \tag{11}$$

where I_k is the investment expenditure in year k, M_k is the operations and maintenance expenditure in year k, I_a is the ancillary expenditure in year k, E_k is the electricity generation in year k, t is the discount rate, and n is the life time of the system.

B. BENEFIT

The stored power in the ESS, which is connected to the PV, is purchased as electricity at the Korea Power Exchange (KPX) for the power distribution business. The electricity sales price is the sum of the SMP and the REC. The PV power is supplied to the grid through the ESS, and when the generated power is larger than the capacity of the ESS, it is supplied directly to the grid without going through the ESS. The amount of electricity sales settled through the ESS is expressed as follows [21]:

$$B_{ESS} = P_{grid1} \times (SMP + REC \times w_1)[\$/\text{kWh}]. \tag{12}$$

In (12), P_{grid1} is the power from the ESS and w_1 is the weighting factor of power sold through the ESS. When the amount of generated electricity exceeds the ESS capacity, the electricity sales amount is expressed as follows:

$$B_{grid} = P_{grid2} \times (SMP + REC \times w_2)[\$/\text{kWh}]. \tag{13}$$

In (13), P_{grid2} is the power from the PV inverter output to the grid and w_2 is the weighting factor of the power sold directly to the grid.

C. ECONOMY ANALYSIS

The predicted and assessed PV power generation is the capacity of the ESS. The range of the capacity is between the minimum and maximum values of PV power generation.

$$P_{PV-min} \leq P_{ESS} \leq P_{PV-max} \tag{14}$$

In (14), P_{PV-min} and P_{PV-max} are the minimum and maximum PV power, respectively. When the minimum and maximum values are plotted in a linear relationship, the x-axis can be regarded as the period and the y-axis as the amount of power generated. In addition, when the NPV is calculated to be the same as the construction cost of the ESS and the amount of electricity sales during the lifetime of the system, the optimal capacity becomes a point at which the NPV value changes from a negative value to a positive value.

IV. CASE STUDY

A. PV POWER PLANT

The PV farm studied is located in the city of Goheung (latitude N34.6, longitude E127.3), in the province of Jeonnam, South Korea. The PV farm is ground-mounted as a fixed type with 1.3-MW capacity; the inclination angle is 30° and azimuth 0°. The PV farm consists of 4,320 sheets of 300 [W] PV multicrystalline modules arrayed in three lines. The power conversion circuit consists of three branch circuits with three 500 [kW]-class inverters and boosts the high voltage to connect to the grid. The acquired irradiation of the inclined planes, module surface temperatures, DC output, and AC output data have been obtained for one year (2017).

B. ESTIMATION OF COSTS AND BENEFIT

The optimal sizing problem can be solved by balancing the benefit and the cost. The sizing problem includes the determination of the power rating and the energy rating [22]. The construction cost of the ESS consists of the costs of the PCS, battery, grid connection facilities, electric wiring, etc. The operation and maintenance cost are estimated as 1% of the construction cost for 1 year. A lithium-ion battery is used and is replaced once during its lifetime of 15 years. All costs are calculated in terms of the NPV with a discount rate of 6.5[%].

The benefit is defined only in the electric power sales amount, as shown in (12). The prices of the SMP and the REC are the trading prices in January 2018 of 0.08 [$/kWh] and 0.1 [$/kWh], respectively. The applied cost and benefit are negative and positive, respectively, according to Fig. 10. The weighting factor of the REC is 1.34, and the minimum capacity of the optimum ESS is calculated as in (12).

C. ECONOMY ANALYSIS

The government has a policy to spread ESS facilities by applying an REC weighting of 5.0 to the electric sales price.

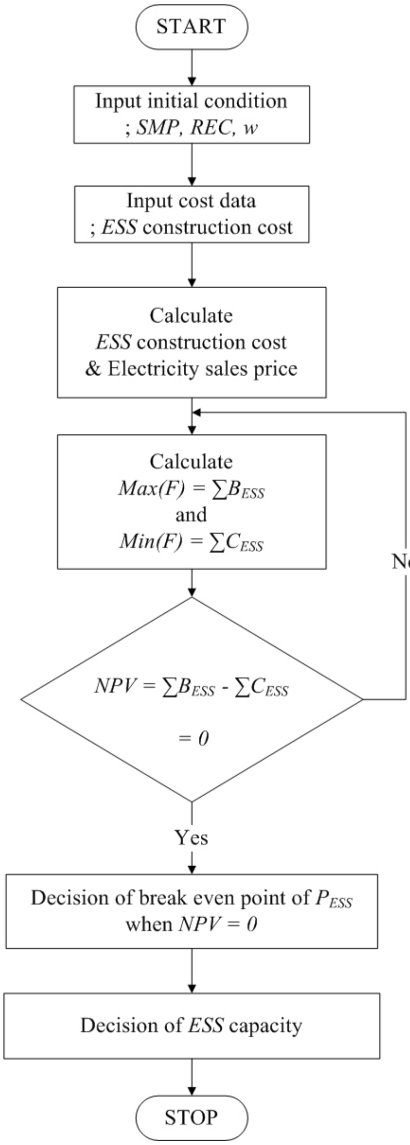

FIGURE 9. Flow chart of optimum ESS capacity.

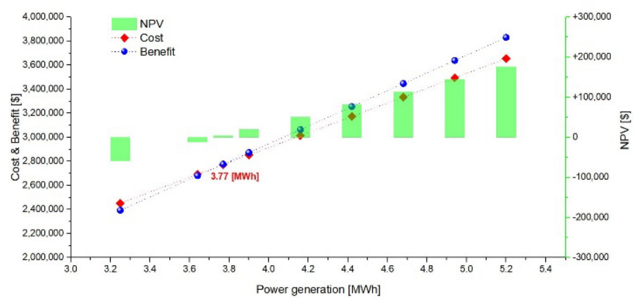

FIGURE 10. Costs and benefits vs NPV at REC 1.34.

The economic point shows a minimum REC weighting factor of 1.34, the equivalent to the cost and benefit at a point where NPV is 0. When PV power is 1.3 [MW], the optimum ESS capacity is at a point where the REC weighting factor is

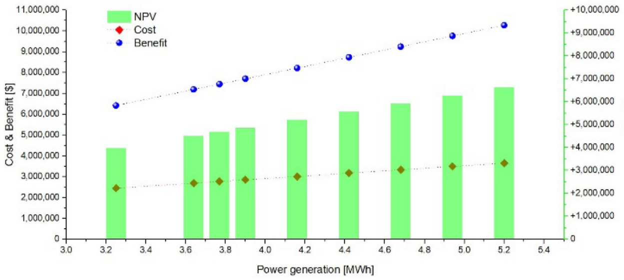

FIGURE 11. Costs and benefits vs NPV at REC 5.0.

1.34 and the optimum capacity is 3.77 [MWh], and the NPV value turns from negative to positive. The optimum point of the ESS is equal to PV generation over 2.9 [h]. This is less than the average generation hours, which is 3.4 [h] in Korea. When the REC weighting factor is applied as 5.0, the electricity sales price raises 2.68 times over that without the ESS. Thus, the electricity sales price is effectively tripled.

D. EXPERIMENTAL ANALYSIS

In Fig. 12, PV power plant performance is presented for January to December 2017. Two histograms show the ESS power and the directly dispatched power from the PV inverter to the grid each month respectively. ESS input powers are charged from 10:00 AM to 4:00 PM every day.

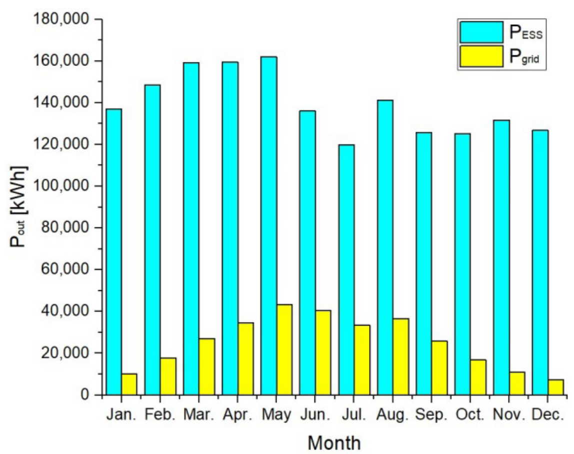

FIGURE 12. Histogram of P_{grid} and P_{ESS} each month.

The predicted optimum capacity of the ESS was 3.77 [MWh], whereas the experimental result was minimum 4 [MWh], as shown in Fig. 12. The result shows that the theoretical prediction approaches the experimental value with error rate of 5.75%.

V. CONCLUSION

A distributed power generation system uses an intermittent power source that provides low power, and it cannot be centrally controlled from the perspective of the system operator. However, a distributed power source equipped with an ESS is equated to a large power source, which can be centrally controlled. An algorithm for the optimum capacity of an ESS was proposed in this work to remove the following disadvantage of distributed power sources: battery costs account for maximum 70% of the total ESS construction cost.

The economic aspect showed a minimum weighting factor of REC 1.34 for the equivalent cost, and the benefit was a point where NPV is 0. When PV power was 1.3[MW], the optimum ESS capacity was at a point where the REC weighting factor was 1.34 and the optimum capacity was 3.77[MWh]. The NPV value then turned from negative to positive. Next, the LCOE price was calculated to be 0.21[$/kWh] for an optimum lithium-ion battery capacity.

The results show that while designing the optimum capacity of the ESS, not only the average insolation hour based on weather-related power prediction of the PV system but also the NPV including the REC weighting factor and/or any type of subsidy program to be used regardless of the region and the governmental strategy must be considered.

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